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Urban Scale Variations of Turbulence Parameters and Fluxes

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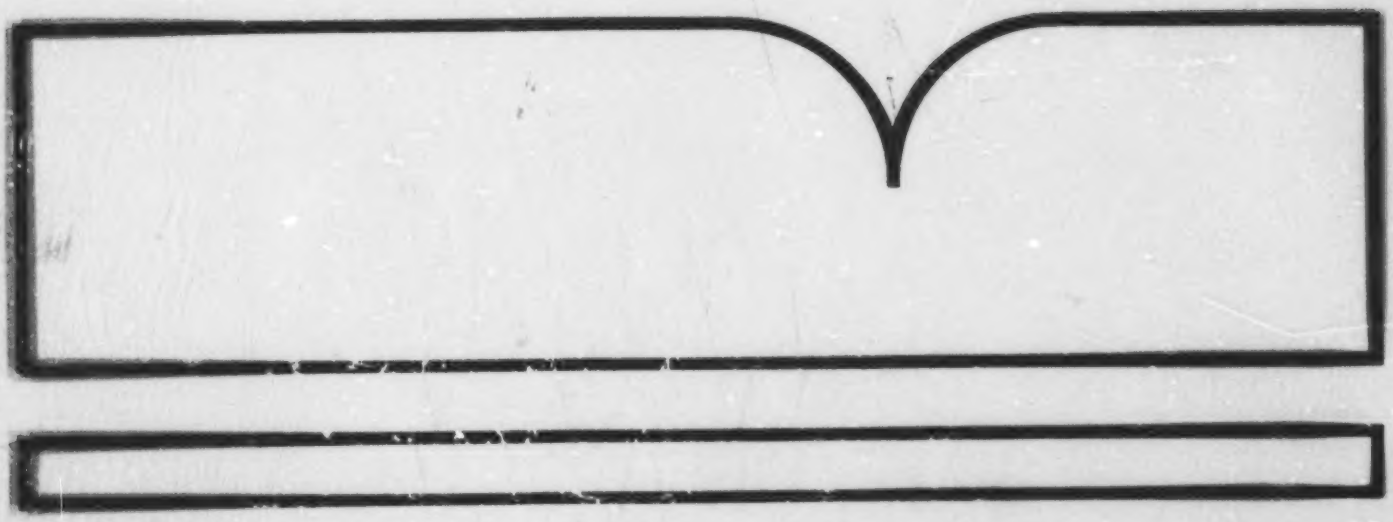

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URBAN SCALE VARIATIONS OF TURBULENCE PARAMETERS AND FLUXES

by

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16. ABSTRACT

Sensible, (H), and latent, (LE), heat fluxes and turbulence statistics in St. Louis, Missouri and the surrounding region are presented. The urban-scale analyses were derived from a series of aircraft transects at 150 m above ground across the metropolitan area during the afternoon convective period. The results revealed that H varied by a factor of two to four in the region; the largest values were associated with the urban heat island. LE varied by a factor of four, but low values of LE overlayed the urban heat island. Consequently, the Bowen Ratio, (H/LE), varied from 1.5 over the city to values less than 0.2 in nonurban areas. The areas along the Mississippi River and adjacent lowlying marshland northeast of the downtown area displayed smallest values of H and Bowen Ratio. The derived surface heat storage term (G) for this area as well as for the urban area exceeded either H or LE. The patterns of σ_u, σ_v and σ_w were similar to that of H, The correlation between the vertical velocity and temperature fluctuations was highest over the city, and a noteworthy minimum was observed in the upwind area over the river and marshlands. The convective similarity relationships for σ_u, σ_v and σ_w appeared to be approximately valid spatially, as variations were typically less than 10% from previous empirical studies except for a 40% anomaly in the lowland around the River basin northeast of the city. The boundary layer over the river area is thus in a state of nonequilibrium

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ABSTRACT

Sensible heat (H) and latent heat (LE) fluxes and turbulence statistics in St. Louis, Missouri and the surrounding region are presented. The urban-scale analyses were derived from a series of aircraft transects at 150 m above ground across the metropolitan area during the afternoon convective period. The results revealed that H varied by a factor of two to four in the region; the largest values were associated with the urban heat island. LE varied across the urban area by about a factor of four, but low values of LE overlayed the urban heat island. Consequently, the Bowen ratio (H/LE) exhibited large spatial variability, with a maximum value greater than 1.5 over the city and values less than 0.2 in nonurban areas. The areas along the Mississippi River and adjacent lowlying marshland northeast of the downtown area displayed significantly smaller H and Bowen ratio. The derived surface heat storage term (G) for this area as well as for the urban area exceeded either H or LE.

The spatial patterns for the standard deviations of the three velocity components ($\sigma_{u,v,w}$), temperature (σ_T), and absolute humidity (σ_q), are also presented. The patterns of $\sigma_{u,v,w}$ were similar to the pattern of H, the highest values associated with the urban heat island. The correlation coefficient between the vertical velocity and temperature fluctuations was highest over the city, and a noteworthy minimum was observed in the upwind area over the river and marshland in association with low H. The convective

similarity relationships for $\sigma_{u,v,w}$ appeared to be approximately valid spatially, as variations were typically less than 10% from theory over the urban area and nonurban region, except for a 40% anomaly in the lowland around the river northeast of the city.

Measurements of H from 30-m towers within various land use areas were contrasted with the aircraft data. Land use differences in H at the surface were at least as large as those observed at 150 m across the city. This was primarily because of the measurement requirement that the minimum resolvable fetch increases with measurement height.

1. Introduction

Air quality, pollutant dispersion, and evolutionary models of the mean and turbulence structure of the mixed layer require information on the surface energy budget fluxes of sensible heat (H), latent heat (LE), and subsurface heat (G). Oke (1982) discussed mechanisms that control the energetics of the urban heat island. The turbulence characteristics of the mixed layer undergo significant modification as air moves across an urban area since there is a coupling between the turbulence and the surface energy and momentum fluxes.

Information on the temporal and spatial distribution of turbulence parameters and fluxes in an urban area is relatively limited. Measurements typically have been derived from time-series data from surface towers at one or more sites, as in Clarke et al. (1982, 1983), Ching et al. (1983a, 1983b), Oke (1978), Nunez and Oke (1977), and Bowne and Ball (1970). These measurements were conditioned by the near upwind fetch and land use characteristics. Hildebrand and Ackerman (1984) compared urban flux and turbulence parameters against rural values using data collected on aircraft for the Metromex study. They show that heat flux and turbulent velocities were larger over the city. They also present data and analyses of the vertical transport of turbulence and also profiles of the fluxes and turbulent velocities over both the urban and the rural areas. However, their measurements cannot resolve the spatial variability of the the UBL. Ching et al. (1983a) discussed the representativeness of a heat flux measurement under convective conditions. They found that the higher the measurement height, the greater the area that the measurement represents. From their analyses, they proposed that a minimum fetch, ℓ_x, or advective time period, ℓ_x/u,

(where u is the mean wind speed) adequately resolved statistically by a measurement made at a height, z_m, is

$$\ell_x = 56\ z_i\ (z_m/z_i)^{3/4} \qquad (1)$$

where Z_i is the convective mixing layer height. This also means that the fluxes for a shorter distance can not adequately be resolved. Furthermore, they demonstrated that the depth of the advective influence for variable land use is directly proportional to the horizontal scale of the phenomenon, or more succinctly, it is inversely proportional to the horizontal temperature gradient.

Ideally, urban heat island and urban climate models require high-resolution information on the temporal and spatial variations of H, LE, and momentum fluxes. Carlson et al. (1981) discussed estimates of H and LE at a resolution of about a kilometer from satellite data that were input into a boundary layer model. However, no experimental data were available for evaluation of the results on that scale. In fact, spatial analyses of these fluxes and their turbulent constituents have not been documented in the literature except for the indications of gross urban and rural differences. This detailed spatial analyses compliments the study of Hildebrand and Ackerman (1984) which emphasized studies of the vertical distribution of the flux and turbulence over a rural and over the central urban area of St. Louis.

An experimental field program designed to measure the turbulence energy fluxes by a fixed-wing aircraft was performed in St. Louis, Missouri by the University of Wyoming during the Metropolitan Meteorological Experiment

(METROMEX) in 1975 and during the Environmental Protection Agency's Regional Air Pollution Study (RAPS) in 1976 using the National Center for Atmospheric Research (NCAR) Queen Air. Some preliminary results were presented by Eaton and Dirks (1977). Spatial analyses of the turbulence parameters and fluxes were based on RAPS data collected along horizontal flight paths at about 150 m above ground. Scales that could be resolved at this altitude were on the order of 10 to 20 km, as determined with Eq. (1). The data base for the analyses included in this paper consists of the aircraft measurements, concurrent turbulence measurements at 30 m on three towers in distinctly different land use locations, surface and upper-air meteorological data, and lidar-derived mixing heights. This paper discusses the spatial distribution of urban and sub-urban scale energy fluxes and related turbulence statistics during the quasi-steady convective period. In addition, the data were examined to determine the extent to which current convective scaling laws (e.g., $\sigma = f(z, Z_i, w'T'$, and w_*) might be applicable in parameterizing the turbulence structure spatially across the urban convective mixed layer. The convective scaling velocity, w_*, is defined as $(g\, w'T'_o Z_i/T)^{1/3}$, where g is gravity, T is temperature (K), and $w'T'_o$ is the covariance of the vertical velocity (w') and temperature (T') fluctuations near the surface. A detailed discussion of the climate and meteorology of St. Louis, with emphasis on the urban induced precipitation as provided in the Metromex Monograph edited by Changnon (1981) provides useful background to this analyses. There are references to spatial patterns of moisture, temperature and wind fields, but not to an in depth analyses of the spatial variability of the energy fluxes and the turbulence statistics.

2. Observational and analytical approaches

2.1 Site description

This experimental program was conducted within the St. Louis, Missouri metropolitan area in August 1976. The area, with its population of 2.4 million, ranked then as the 10th largest Standard Metropolitan Statistical Area in the United States. The metropolitan area is centered southwest of the confluence of the Missouri and Mississippi Rivers. The population of the city itself was about 0.6 million. The average elevation of the city is 150 m above mean sea level (MSL). The region along the rivers and an extensive area to the east of the urban area, known as the American Bottoms, are about 125 m MSL. From the American Bottoms, elevation increases to 160 m MSL toward the northeast, east, and southeast. The elevation and variability of terrain increase beginning about 20 km southwest of downtown St. Louis. The highest terrain was 40 km southwest of downtown St. Louis at an elevation of 190 m MSL. Thus, the total relief across the study area is about 65 m.

Figure 1 displays a land use map of St. Louis. This is the same map shown in Auer (1978), except for a reduction in the number of land use classes (See Table 1 in Auer (1978) for the detailed description of each land use class).

2.2 Measurements and data processing

The aircraft flight pattern used during the experimental studies is shown in Fig. 1. The aircraft was equipped with an inertial navigation system, a gust probe system mounted on a boom ahead of the aircraft, and an on-board computer for digital recording and real-time display of measure-

ments. More details about the sensors and data acquisition system are provided by Lenschow et al. (1978). The fast-response measurement system was capable of providing rapid fluctuation data of the three dimensional winds, temperature, and absolute humidity. The data were collected at a sampling rate of 16 s^{-1}. In addition, altitude and surface radiometric temperature measurements were obtained at a rate of 1 s^{-1}. The average flight altitude was 150 m above ground. Because of terrain variations, the actual height of the aircraft above ground varied from 110 m southwest of the urban area to 175 m in the regions along the rivers and in the American Bottoms.

We determined from Eq. (1) that a horizontal flight segment of about 20 km was required for flux measurements at a height of 150 m. This requirement was satisfied with five minute segments, since the aircraft speed was 75 m s^{-1}. As a consequence, small scale variations are effectively filtered out while variations on the urban scale remain. The data for each flight run were processed and further smoothed using three minute forward overlapping of the five minute segments. The location of the center of each segment is shown in Fig. 1. A flight pattern required approximately 1.5 to 2 hours to complete. During this time period, some temporal change occurred in all the measured variables. These variations, while believed to be small, were not taken into account and as a consequence, a limited amount of 'temporal noise' is inherent in the spatial analyses.

A linear trend was removed from the time series of each segment. The turbulence statistics and fluxes were computed from the detrended data. The velocity components were transformed so that u represented the alongwind

component and v the crosswind component for each segment. Details of the data processing and some preliminary analyses can be found in Godowitch et al. (1981).

The aircraft altitude also varied along the flight path in response to vertical motions associated with thermal convection. In computing H for a flat surface, the temperature deviations due to departures from a mean flight altitude were compensated based on a dry adiabatic gradient. No adjustments were made to the vertical velocity, or to moisture fluctuation data, since the vertical gradients of both parameters in the mixed layer were characteristically small. The average H computed from the adjusted temperature data was around 6% greater than values computed without the temperature correction. The rationale for the temperature adjustment is as follows: typically, for a positive heat flux through a horizontal surface, warm air anomalies (thermals) are associated with upward motions and cold air anomalies with sinking motions. The aircraft responded to these vertical motions with excursions of about 25 m from the average flight level when it penetrated thermals. Without adjustments for these altitude variations, cooler temperatures were recorded for updrafts and warmer air temperatures for downdrafts due to adiabatic expansion and contraction processes. The net result was a slightly reduced covariance.

2.3 Effect of flight path orientation on spatial analyses

We were concerned that the orientation of the flight paths, from which the spatial fields were obtained, may not have adequately represented two-dimensional areal measurements required for proper spatial analyses because the land use distribution and land composition below each flight segment

were unique. Thus, the design of the flight pattern might have biased the conclusions from the analyses.

This sampling bias would not be expected to be large under horizontally homogeneous conditions. In urban areas or other regions where surfaces exhibit a mosaic of land uses superimposed on natural variations, such as water bodies and other terrain features, the limitations of aircraft sampling to represent areal measurements required an examination.

Aircraft measurements obtained from mid-day flights on both 13 and 19 August, and 2 flights on 18 August provided a limited set of data from north-south flight segments that could be compared with values derived from southwest-northeast flight segments. Clearly, the underlying surface features for these flight segments differed. In this analysis, those segments whose midpoints most nearly coincided were compared (Fig 1.). The flight paths intersected over the urban area, near the river, and in a rural location east of the urban area. Hereafter, the urban, river, and rural points are denoted by U, W, and R, respectively. Further, the north-south segments were crosswind (X) and southwest-northeast segments were alongwind (A). The means of the turbulence parameters and the results of statistical comparisons are given in Table 1. Four case studies relate to the quasi-steady convective time period: each was characterized by undisturbed weather with mixed layer mean winds from the east-northeast. The probability, P, of a statistically significant difference between the pair of alongwind and crosswind means from the Student T test is shown.

The results show large standard deviations of surface temperature (σ_{Tg}). In contrast, the standard deviation of temperature (σ_T) at 150 m

was significantly smaller. Large differences in σ_{Tg} were exhibited between segment pairs and among the segments. The most pronounced differences were found between the pairs over the river, where the probability of a significant difference was 99.5%. In fact, the largest σ_{Tg} was observed in the W(X) segment, where the aircraft path had crossed the river several times. The U(A) and W(A) segments also had relatively large values of σ_{Tg}. In these two cases, the segments included a pass over the river and the latter segment made several crossings of Horseshoe Lake. The U(X) segment had the smallest σ_{Tg} even though its σ_T was large. We concluded that the large variations in surface temperature were due to temperature differences between the Mississippi River and adjacent land. Thus, the inclusion of data from the southwest-north east (A) run could complicate spatial analyses in locations near the river.

Table 1. Mixed Layer Turbulence Parameters for Alongwind-Crosswind Pairs

Location	σ_{Tg}	σ_T	σ_q	σ_w	σ_u	H	LE
			Sample Means				
URBAN (X)	3.68	0.16	0.29	1.05	0.92	105	176
URBAN (A)	5.36	0.16	0.25	1.00	1.12	98	130
RIVER (X)	7.05	0.16	0.34	0.96	0.93	50	153
RIVER (A)	5.34	0.13	0.27	0.87	1.08	52	183
RURAL (X)	4.84	0.12	0.29	0.88	0.84	58	230
RURAL (A)	5.16	0.11	0.29	0.83	1.00	46	176
			Differences between Paired Means				
URBAN (X-A)	-1.68	0.004	0.033	0.058	-0.200	7.0	46.0
RIVER (X-A)	1.71	0.025	0.065	0.093	-0.15	-1.25	-30.0
RURAL (X-A)	-0.32	0.018	0.010	0.055	-0.155	12.3	40.0
			Probability That Pairs Differ Significantly				
P urban	0.983	0.20	0.35	0.75	0.92	0.45	0.55
P river	0.995	0.85	0.70	0.92	0.75	0.30	0.40
P rural	0.550	0.75	0.20	0.55	0.70	0.70	0.40

Differences between paired means of σ_T, σ_q, H, and LE were not statistically significant for any of the segments. Except for σ_w (X-A) and σ_w(X-A), which were marginally significant (92%), the paired values of σ_u and σ_w also did not differ significantly. Thus, we concluded that with the possible exceptions of σ_u and σ_w, the spatial analyses of these data would not be unduly biased by the orientation of the flight pattern.

2.4 Meteorological conditions on 18-19 August 1976

A quasi-stationary high pressure ridge dominated the flow from the surface to 500 mb during the experimental period. The center of the surface high pressure system was north of St. Louis at the beginning of the experimental period, and it slowly drifted northeastward. Skies were clear during the day on 18 and 19 August, with the exception of a few fair weather cumulus clouds occurring on the 19th for about 30 minutes around noon, which was prior to the afternoon flight (White et al., 1978). A time-height cross-section of potential temperature, which includes the two case study days, is shown in Fig. 2. The vertical profiles were obtained four times daily by rawinsondes released 40 km southwest of the urban area. The nocturnal surface inversion was eroded by 0900 CST on both days. The mixing height, Z_i, defined as the base of the elevated inversion, was higher on 19 August than on 18 August. This was believed to be due to stronger subsidence on the 18th (Ching et al., 1983c). An analysis of urban-rural differences of Z_i from concurrent profile data obtained at an urban site, 3 km west of the Gateway Arch, and the rural site located 40 km southwest of the urban site, showed little if any difference in Z_i with time and for both 18 or 19 August. Thus, these two case study days did not exhibit a dome of higher Z_i over the urban site, as might have been expected from the studies of Spangler and Dirks (1974). The data of Hildebrand and Ackerman, 1984, do not indicate large urban-rural differences in mixed layer height for their three case study periods. Table 2 lists the hourly values of mean wind speed and direction at 30-m, Z_i, and net radiation, Fn. Fn measurements were obtained by averaging data at 30 m from an urban industrial site near the downtown area and a rural site, 10 km east of of the

downtown center. Fn and wind direction are seen to be quite similar on both days, while wind speeds were slightly higher on the 19th. The mean wind speed for each of the aircraft segments was practically uniform across the domain on both days. On 18 August, the mean wind over the domain was 3.1 m s^{-1} with a standard deviation of 10% of the mean, while on the 19th, the mean wind speed was 3.5 m s^{-1} over the region and a standard deviation of 8% of the mean. A comparison of winds at 30-m and at the 150-m level showed little wind shear. Measurements of Fn at both sites were averaged because the differences between the two values were small. This was consistent with the findings of White et al. (1978) whose aircraft measurements of Fn indicated little spatial variability during the convective period of the day. Thus, because these two days were meteorologically very similar, we decided to compare various spatial analyses and magnitudes of turbulence parameters for the two days.

Table 2. Hourly Means of Meteorological Variables

DATE TIME	WIND SPEED ($m\ s^{-1}$)	DIRECTION (degrees)	Z_i (km)	Fn ($w\ m^{-2}$)
8/18				
11	2.9	110	0.9	505
12	2.5	100	0.95	515
13	2.6	95	1.0	505
14	1.9	100	1.0	450
15	2.8	75	1.0	350
16	3.2	75	1.0	225
8/19				
11	2.8	105	1.0	500
12	2.9	90	1.3	505
13	2.8	85	1.4	475
14	3.2	80	1.5	425
15	3.5	80	1.5	330
16	3.7	85	1.6	220

3. Results

3.1 Mean fields

The surface temperature pattern on 18 August is shown in Fig. 3. This spatial analysis was derived from data collected by a downward-looking infrared radiometer. An example of the time series data for one flight leg is also presented in Fig. 3. A fairly symmetric urban scale ground temperature anomaly of 10°C was observed between the downtown area and the surrounding rural areas. The highest average urban value was 38.5°C. An

urban surface temperature anomaly of about 10°C was also found on 19 August, with the same spatial features, but with a highest average urban surface temperature of 40.5°C. These peak values are comparable to those reported by Vukovich (1983). The analysis method filtered out land use scales smaller than about 20 km. Hence, the smaller than urban or sub-urban scale land use features were not resolved. However, the time series data showed large variability in the surface temperature across the region, superimposed on the larger urban scale variation. Lowest temperatures of 23°C occurred around the Mississippi River and Horseshoe Lake. These temperatures contrasted sharply with the warmer temperatures of the adjacent land. Vukovich (1983) also noted similar large land-water temperature differences in the same regions. Ching et al. (1983a) suggested that these pronounced variations were responsible for the low-level positive H anomalies downwind of the land-river interface. Mean temperatures at 5 m from the 25-station Regional Air Monitoring System (RAMS) during the three hour period of the flight were also spatially analyzed. A surface-air temperature difference (DTz) field was then derived by graphical subtraction of these interpolated temperature patterns. The results for 18 August are shown in Fig. 3. The DTz was 11°C over the urban area, but DTz values decreased outward from the city to about 1°C in the rural environment. The temperature difference pattern was similar to the surface temperature pattern because the 5-m temperature measurements varied by only about a degree over the region at this time. These very large urban DTz's should be associated with a positive urban H anomaly. The urban scale horizontal surface temperature gradient averaged about 0.3°C km^{-1} on both 18 and 19 August, which was fairly large since that is about 30% of the dry adiabatic gradient.

The spatial analyses of temperature and absolute humidity (q) at 150 m on 18 and 19 August are presented in Fig. 4. The temperature fields display an urban-induced positive anomaly that was displaced downwind of the surface temperature maximum. The anomaly was 1°C on the 18th and 1.4°C on the 19th, about an order of magnitude smaller than the radiometric surface temperature anomaly associated with the urban area. Note that this analysis was based on data at a constant altitude above sea level. Temperature adjusted to 150 m above ground level was also analyzed by accounting for the terrain elevation below the aircraft and by assuming a dry adiabatic gradient. On this terrainfollowing surface, the positive temperature anomaly was smaller and shifted even farther west.

The spatial pattern of q on 18 August revealed a positive anomaly of 0.5 g m^{-3} over the urban area superimposed on a pattern mean of 9.1 g m^{-3}. A relatively dry region was observed over Granite City, northeast of the city. The "moist" urban island differed from the "dry" island reported over St. Louis by Sisterson and Dirks (1978) and Dirks (1974), although the wind speeds in our two cases were greater than those in the weak flow cases in Dirks (1974). On 19 August, the average q over the region was 10.5 g m^{-3}, an increase of 1.4 g m^{-3} since the previous afternoon. This was probably a result of the synoptic influence. Spatially, the pattern was more complicated on the 19th, but the urban area appeared to be slightly drier than the surrounding region. The moister areas were northeast and southeast of the downtown area. The results in these cases suggested that the moisture dynamics were induced by a combination of synoptic scale variability superimposed on urban-induced moisture transport processes. A more detailed examination of the moisture distribution and temporal

changes can also be found in the preliminary efforts by Dzurism and Hilberg as reported in Changnon 1981 wherein the urban area generally tends to be drier than the surrounding rural areas, but patterns are not easily related to land use types. Sisterson and Dirks (1978) suggest that the drier urban surface and the enhanced mixing contributed to cause of the relatively dry urban boundary layer.

3.2 Turbulence parameters

This section describes the spatial fields of the standard deviations of surface (σ_{Tg}) and air temperature (σ_T), absolute humidity (σ_q and velocity components ($\sigma_{u,v,w}$). Figs. 5a and 5b depict σ_{Tg}, with values ranging from 3°C to 7°C. The largest values were observed near the urban area, but the maximum on both days was found in the region along the Mississippi River, the downtown area, and around Horseshoe Lake. A flight path was nearly parallel to the river. On the other hand, small values of σ_{Tg} were northwest of the city. The flight paths crossed the rives, but the low values probably reflected the fact that the width of the river was a small fraction of the overall flight segment. Thus, the large temperature contrasts between land and water were not observed. As discussed above, analyses of this parameter could be strongly biased by the orientation of the flight paths. Thus, the fine details of this analysis are inconclusive. Nevertheless, the general finding of a larger σ_{Tg} in the urban area is of interest.

The pattern of σ_T was complex, as revealed by Figs. 5c and 5d. Overall, σ_T was larger over the urban area than far from the city. Furthermore, there is an indication of a maximum σ_T along the river where σ_{Tg} was also large.

Relatively large σ_T's were observed downwind of the urban area, which suggests that greater turbulent temperature fluctuations emanated from the urban area. Values of σ_T were an order of magnitude smaller than those of σ_{Tg}. The mean σ_T at 150 m over the region on 18 August was 0.14°C compared with a corresponding mean σ_{Tg} of 4.3°C, which is a factor of 30 larger. Similarly, σ_{Tg} was larger than σ_T by a factor of 35 on 19 August.

The spatial variability of σ_q for both cases is shown in Figs. 5e and 5f. The mean σ_q over the region was 0.31 on the 18th and 0.34 g m^{-3} on the 19th. On the 18th, the urban area exhibited a broad region of small σ_q; the minimum value was 0.2 g m^{-3}. Low values were also observed both north and southeast of Horseshoe Lake. One might also consider the region downwind of St. Louis to be associated with smaller values (i.e., part of an urban turbulence plume). On the 19th, an area of small σq values was located over Forest Park (FP), a significant land use feature about 10 km west of the Gateway Arch, but maximum values were found over the downtown area. The patterns for q and σ_q did not appear to be correlated. The relatively moist urban region corresponded to small σ_q on the 18th. There was also no evidence that the spatial patterns of q and σ_q on the 19th were correlated.

The velocity standard deviation fields are shown in Fig. 6. All three components generally exhibited relatively large, if not maximum, values over or downwind of the urban area. In addition, the magnitude of $\sigma_{u,v,w}$ were similar (about 1 m s^{-1}). On 18 August, a maximum σ_u of 1.05 m s^{-1} was observed slightly downwind of the city. On the 19th, the largest σ_u was farther downwind. The average σ_u over the region was 0.9 m s^{-1} with a range from 0.80 to 1.05 m s^{-1} on 18 August. On the 19th, the average σ_u

was 1.03, with values ranging from 0.9 to 1.2 m s^{-1}. The average σ_v over the region was slightly greater than the average σ_u; differences were 14% and 17% on the 18th and 19th, respectively. The average σ_w over the region on both cases was 0.9 m s^{-1}. The spatial variation of σ_w was very similar to σ_u on both days (i.e., a region of maximum values slightly downwind of the city on the 18th, whereas the maxima were farther downwind and elongated on the 19th). Hildebrand and Ackerman (1984) observed 20% to 40% larger σ_w than σ_u or σ_v in urban areas, which was not observed in these results. Moreover, at comparable altitudes, they observed urban values of σ_w to be routinely two to three times as large as rural values, which were conserably larger than the nominal 50% urban enhancement observed in this study.

3.3 Fluxes

Figure 7 depicts two time series of w'T' measured on 18 August. They are from a north-south flight segment in the vicinity of the river near Granite City (7b), and a north-south segment centered over the urban area (7a). The beginning times of the measurements were 1423 and 1439 CST, respectively. Many large thermal eddies were distributed evenly over the urban segment. These data suggest a quasi-stationary type record. The average H of the urban segment was 105 w m^{-2}. In contrast, the segment in the region over the river contained fewer, intermittent thermals, with the largest fluctuations occurring near the start of the segment and at the end (south), which corresponded to the downtown area next to the river. The major portion of this time series segment showed weak correlations between w' and T'. Therefore, thermal eddies were irregular and less vigorous than over the central urban area. The average H of this segment was only 21 w m^{-2}, one fifth that of the urban segment. The relative quiescent time se-

ries was primarily associated with the river and adjacent low-lying flood plain. On average, H would be even smaller in this segment if the portion of the record containing the relatively larger covariances at the end of the time series were omitted.

The spatial analyses of H are presented in Fig. 8a and 8b. The average H over the region for both days was 63 w m^{-2}. However, broad areas of larger H were found over the urban area, with the center of the maximum about 10 to 15 km downwind of the Gateway Arch on both days. Interestingly, the maximum H was essentially over or slightly downwind of the maximum of surface temperature and temperature difference noted in Fig. 3. A region of small H was observed in the vicinity of the river and Granite City, the same region as the north-south segment that provided the results in Fig. 7a above. This feature was present on both days. In fact, the same result was observed in all other experimental cases with an easterly wind flow. The evidence suggested that when upwind, the region to the northeast of the city exhibited a pronounced minimum H at 150 m, while the maximum H was downwind of the downtown area. The minimum and maximum values were oriented along a southwestnortheast axis. On average, the gradient of H for both days was 4 w m^{-2} km^{-1} between extremes. Larger gradients, 15 w m^{-2} km^{-1} or more, have been measured near the river (Ching et al., 1983a). The evidence suggests a region of small H along the path of the rivers, but this could not be confirmed with the measurements from this particular flight pattern.

The spatial analysis of q flux is shown in Figs. 8c and 8d. On 18 August, the average LE over the region was 207 w m^{-2}, with fluxes for individual segments ranging from 70 to 330 w m^{-2}, and on the 19th, the average

LE was slightly greater (232 w m^{-2}) with individual values varying from 130 to 360 w m^{-2}. A well-defined region of small LE was observed less than 10 km downwind of the Gateway Arch on the 18th. The pattern on the 19th showed a broad region of low LE, but areas of large LE within the urban area to the south. These moisture flux anomalies were in the proximity of the river, and it appears that the river could have been important in partitioning the energy fluxes. Relatively large values of LE were observed 10 km south of the Gateway Arch on both days, but LE was much higher on the 19th. The patterns for LE exhibits greater spatial complexities than for the heat flux.

In the urban area, LE was comparable to H, whereas in locations away from the urban area, LE was the dominant flux. The strong influence of the river in suppressing H did not appear to affect LE in any consistent manner.

It was of considerable interest to evaluate the remaining term in the surface energy budget, the ground heat flux, G (Nickerson and Smiley, 1975). In this case, G was derived as the residual from the evaluation of the other measured terms in the energy budget (i.e., G = Fn-H-LE). We assumed that: LE was invariant with height from the surface to 150 m, H varied linearly with height, and Fn was uniform across the region, but varied with time. The first assumption required that the time rate of change of q within a parcel moving across the domain was negligible, or that a balance was reached between the local rate of change and the advective component of q. The second assumption meant that the diurnal temperature change occurred uniformly with altitude, and the last assumption was justified on the basis of observation and analyses of aircraft measurements of Fn, which indicated

its spatial variability did not exceed 5% over St. Louis (White et al., 1978). The Fn values from concurrent measurements at urban site 105 and rural site 109 were averaged. The differences between Fn at these sites was indeed small, but the temporal variations were significant over the duration of the flights.

The accuracy of the derived estimate of G from the budget method and the low level aircraft data is further limited at least by the accuracy of the method to calculate the surface values of H and LE. An estimate of this uncertainty is discussed. The vertical gradients of H and LE are proportional to the time rate of change of enthalpy (pC_p T) and moisture, respectively. Consequently, uncertainties attributable to extrapolation procedures were limited to uncertainties in the magnitude of temporal changes. If we assume a factor of two uncertainty in the heating rate, then the resultant H at the surface from aircraft data at 150 m (i.e., about $0.1Z_i$) yields an uncertainty of between 10% and 20%. Typically, rates of change of moisture are at least one order of magnitude smaller than the corresponding enthalpy changes during the day, so that the relative magnitude of the uncertainty in LE will be considerably less than that for H. For example, given H and LE of order 100 w m^{-2} and 250 w m^{-2}, the corresponding uncertainties are about 10-20 w m^{-2} for H and less than 10 w m^{-2} for LE. These uncertainties are much smaller than the spatial variations of G shown in Figs. 8e and 8f.

The most pronounced feature in both cases is the large amount of heat (large G) stored in areas within and adjacent to the Mississippi River, especially around Granite City and toward the confluence of the rivers. The

analysis also indicates that the downtown area stores greater amount of heat at this time than in the downwind urban locales, where G was small. These results are consistent with the study by Doll et al. (1983) which shows that on average, G changes sign from positive to negative during mid-afternoon (i.e., 3 to 4 PM), which is the same time period as the 18 August case study. Note that day to day variability of the time when G changes sign can be large as exemplified in Doll's study. Thus, small values in the rural area downwind of the city and the larger value of G in the upwind rural data are not inconsistent. The area southwest of the Gateway Arch on the 19th showed a release of ground heat, presumably to balance the large values of LE.

The Bowen ratio, H_o/LE, where "o" denotes the surface value, reveals the relative importance of these fluxes in the energy balance. Figure 9 shows the spatial analysis of the Bowen ratio derived with the extrapolated H_o. On the 18th the heat flux was dominant in the urban area, as the Bowen ratio was at a maximum about 5-10 km downwind of the Gateway Arch. Values were greater than 1.8 in this area; whereas values of 0.2 were characteristic of various rural locations. Low Bowen ratios for rural areas were also observed over moist cultivated fields in Tennessee and Kentucky (Ching et al., 1983b). These low values are comparable to tropical ocean values. On the 19th, values were greater than 0.8 in the same area as the maximum on the 18th. Bowen ratios were anomalously low in the vicinity of Granite City, primarily because of small heat flux. Minimum values of 0.2 were also observed in rural locations on the 19th.

Another derived parameter of interest is λ (G/Fn). Nickerson and Smiley (1975) used λ in a planetary boundary layer model. Later, Deardorff (1978) evaluated a λ scheme in evapotranspiration mixed layer models and found the parameterization highly accurate in modeling the evolution of the mixed layer. Doll (1983) and Doll et al. (1983) analyzed the diurnal and seasonal variation of λ as a function of subsurface moisture content and different surfaces. A strong diurnal variation in λ was found for concrete and soil, with values of 0.2 to 0.6 characterizing the afternoon period. However, magnitude and even sign changes occurred during the afternoon. Results from Oke (1982) and Oke et al. (1981) suggest a range for λ of 0.25 to 0.3 in urban areas during the day.

The derived values of G and measurements of Fn were used to compute λ. The results are shown in Figs. 9c and 9d. Clearly, large variations in λ appeared in the urban area, with very large values indicated along the river. Large λ's also appeared over the main downtown area. Downwind of the urban center, λ decreased. Values of about 0.1 to 0.3 generally characterized urban locations downwind from the downtown area. These values are consistent with the results of Oke (1982)and Oke et al. (1981), although they exhibit a slightly larger range. On the other hand, such a range is consistent with the data from Doll et al. (1983).

4. Discussion

The large values of H over the urban area were anticipated. Generally, the urban-rural differences were similar to those observed by Hildebrand and Ackerman (1984). The very low values over the river basin areas, lower than even the rural values were unexpected, but the evidence for these low

values was strong. Unusually low values of σ_w and σ_T were not found in these areas. Thus, we concluded that the correlation between temperature and vertical velocity fluctuations was quite variable across the urban region. To substantiate this, the correlation coefficient for w' and T' was determined from $r_{wt} = w'T'/\sigma_w\sigma_T$. The results are presented in Fig. 10. The average r_{wt} over the region was 0.52 on both days. The urban area clearly exhibited a greater correlation between warmer air (+T') and upward motions (+w'). On both days, r_{wt} in the urban area was about 0.6 or greater. In contrast, r_{wt} was small over the river areas, with a minimum in the Granite City area. The maximum and minimum values differed by a factor of 4 on the 18th and by about a factor of 2 on the 19th. We postulated that the water being colder than the land, was actually a heat sink, and the small but positive H at 150 m reflected advection rather than local heat flux production in this area.

Convective similarity relationships given by Caughey and Palmer (1979) for σ_w and σ_T predict $r_{wt} = 0.56$. The maximum r_{wt} was greater over the urban area which suggests that the turbulent components of the vertical velocity and/or temperature were not in local equilibrium with the enhanced H over the urban area. Briggs (1983) suggested a start-up scale for turbulence from a step change in H to be $2Z_iU/w_*$, which is about 5 km or more. The urban H maximum is located just downwind of the maximum in r_{wt}, which suggests that the largest region of nonequilibrium to be in the vicinity of the largest horizontal gradient of H.

The correlation coefficient between w' and q', r_{wq}, was analyzed in a similar manner. The average r_{wq} over the region on both days was 0.3. The

spatial analysis is shown in Figs. 10c and 10d. In general, the variation of r_{wq} on both days was similar (i.e., urban area contained the smallest values). Minimum values in the urban segment were 0.13 on the 18th and 0.16 on the 19th. In contrast, rural values of 0.5 or larger were observed. Although r_{wq} was smaller in the river region than in the upwind rural areas, there was no anomaly in r_{wq} comparable to that observed in r_{wt}.

In light of the complexities and inhomogeneities of the turbulence fields, we examined the feasibility of scaling the turbulence in the urban convective mixed layer. Recent theories and results of measurements over nonurban, relatively homogeneous surfaces have demonstrated that the turbulent wind and temperature statistics can be scaled by $w*$ and $\theta*$ ($w'T'/w*$) in the convective boundary layer (Caughey and Palmer, 1979). In the surface layer, σ_w varies with z/L (L is the Obukhov length), but σ_w approaches the same magnitude as σ_u and σ_v in the middle of the convective layer. Mixed layer scaling is approximately applicable at $z>=0.1Z_i$. Thus, $\sigma_u=\sigma_v=\sigma_w=Aw*$, where A has been experimentally determined to be between 0.6 and 0.7. A flight altitude of 150 m satisfied the z/Z_i criterion for testing the mixed layer scaling relationship because Z_i was 1 km and 1.5 km on the 18th and 19th, respectively. The values for $w*$ were computed with the extrapolated H_s values described above. The spatial analyses of $\sigma_{u,v,w}/w*$ are presented in Fig. 11. The mean values over the region and their standard deviations are given in Table 3. The extreme values over the sets of values are in parentheses.

Table 3. Means and standard deviations of scaled velocity component σ

	18 August	19 August
$\sigma_u/w*$	0.71±0.09	0.72±0.08
	(0.95)	(0.95)
$\sigma v/w*$	0.82±0.11	0.84±0.09
	(1.06)	(1.01)
$\sigma_w/w*$	0.70±0.07	0.65±0.06
	(0.92)	(0.83)
z/Z_i	0.15	0.10

The results for $\sigma_u w/w*$ and $\sigma_w/w*$ were comparable to but slightly larger than most values in the literature (Caughey and Palmer, 1979). However, the cross-wind component scaled results were even slightly higher. The scatter of values was fairly small, probably because the σ's were only 9% to 13% of their means. The small scatter was apparent in the spatial analyses, except along the Mississippi River and in the Granite City area. Fairly uniform values were observed across most of the region. This was certainly true over the urban area, where deviations from these scaling relationships might have been expected. The anomaly in the area around the river was obviously a result of the small H. For the three σ's, the scaled means for the river area were 20% to 35% higher than the regional means.

The vertical profile of H appeared to vary more rapidly near the surface than aloft. Hence, the method of extrapolating H at 150 m to the surface probably underestimated the value of H_o. For diagnostic purposes, if we assume that H is zero at $0.5Z_i$ and its variation is linear above the surface, a

larger H_o is derived. This alternate method of estimating H_o would increase w_* by 6%, which would mean a 6% reduction in the values in Table 3 and Fig. 11. These values would be closer to previously reported results (Caughey and Palmer, 1979).

Convective similarity predictions appear general enough to apply over urban areas, as verified by the aircraft measurements. This result should be examined further. However, there is evidence that convective scaling may not apply for measurements whose resolution is on the land use scale or smaller. Ching et al. (1983b) showed, for RAPS site 105 under easterly flow, that σ/w_* was 0.47, significantly lower than the current estimate of 0.6-0.7. They attributed this to an anomaly in w_*, because a large component of H at this site compensated for cold air advection off of the Mississippi River, less than 1 km upwind of the site. Further, as Briggs (1983) argues, the distance from the river to the measurement site was of insufficient fetch to release the increased potential energy available in the increased H_o. The response distance for changes in H_o is $2Z_iU/w_*$ or about 5 km. Thus, turbulence parameterizations based on experience in more ideal homogeneous locations are only partially valid for urban and land use inhomogeneous areas due to nonequilibrium of the turbulence to the large change in H_o.

The preceeding discussion prompted an examination of measurements obtained at two different heights in the urban area. Eq. 1 established the criterion developed by Ching et al. (1983) for the minimum upwind fetch resolvable by a measurement made at z_m. Under ideal, homogeneous conditions and over a uniform surface, the surface H is the sum of the flux measured

at z_m plus the integrated heating rate of the intervening layer. In urban areas, however, measurements of H at z_m represent a larger upwind fetch area than near the surface, an extrapolation of this measurement to the surface will in general not be the same as a measurement at the surface. This problem is illustrated in Fig. 12, which shows the temporal variation of hourly averaged values of H from three 30-m towers and H at 150 m taken from the spatial analyses during concurrent periods on 18 and 19 August. Because the analysis was based on aircraft data obtained over a short but finite period, H from aircraft measurements was plotted to represent the entire period of the flight. Tower data were missing for periods of system maintenance. For 18 August, results for two different flights are shown, while additional values from another flight on the 19th are plotted.

The tower at site 105 was in an urban/commercial area with a large fraction of paved surfaces approximately 3 km southwest of the Gateway Arch and 1 km west of the Mississippi River. Site 107 was situated in an urban residential area about 6 km northwest of the downtown center. The surrounding area was composed of two to three story dwellings and numerous trees. Site 109 was in an agricultural area about 10 km east of the downtown center. More detailed descriptions of these sites and instrumentation are given in Clarke et al. (1982) and Ching et al. (1983). From Eq. (1), we determined that the measurements at 30 m represent turbulence generated over an upwind fetch of about 4 km; whereas at 150 m, the minimum fetch was about 15 km.

The results revealed large heat fluxes at site 105, which were explained by Ching et al. 1983) as a consequence of cold air advection from the river

under easterly flows. The river temperature was about 20°C lower than the adjacent land temperature. Furthermore, this feature was expected to be shallow, as the advective effect could not be detected at the aircraft level. The interpolated H at 150 m was indeed much smaller than the tower measurements. An increase of 20% or even somewhat more, as might be required to support nonlinear and larger low-level H gradients below 150 m, was still insufficient to explain the difference in H between these two heights. The magnitude of the difference, though largest at site 105, was also very large at the other two sites. These results demonstrated that measurements of H on the land use scale can be substantially different than the urban scale heat flux obtained at greater altitudes. This implies that the land use variations in the other terms of the energy budget generally will be considerably larger compared to the large-scale averages obtained at aircraft flight levels.

5. Summary and conclusions

The results presented were derived from case studies of two consecutive days of aircraft and tower turbulence measurements in the St. Louis urban environment. The meteorological conditions on both days were nearly the same in most respects during characteristic undisturbed fair weather summer convective afternoon periods. Consequently, many spatial variations of energy fluxes and turbulence statistics were similar for both cases, which increased confidence in the following major conclusions:

1. In the urban area, H was generally enhanced, while LE was generally lower than in the surrounding rural areas. Consequently, the Bowen ratio was largest over the urban area.

2. A pronounced minimum in heat flux was consistently observed over the Mississippi River and lowlying areas around Granite City. The results suggested that low H could be expected along other stretches of the rivers, but possibly not as pronounced as that found northeast of St. Louis.

3. The correlation between vertical velocity and temperature fluctuations was largest over the urban area, and unusually small over the river basin and nearby marshland in the flood plain northeast of downtown St. Louis. This implied greater coherence between w' and T' in the urban area. On the other hand, we suggest that w' and T' measurements were mostly in quadrature (i.e., out of phase) in the river region, where r_{wt} was at a minimum.

4. Derived G values were largest in the area around Granite City and in the downtown area, where G/F_n was about 0.6.

5. Convective scaling results for the velocity component standard deviations agreed with the results of other experiments, even in the urban region. Values differed sharply from convective scaling relationships in the river region and over Horseshoe Lake.

6. Measured H_s and extrapolated H_s values were different for measurements at two different altitudes; this was expected, because the minimum upwind areal extent resolvable by a measurement increases with height, and because H varied greatly in different land use areas.

Note that the spatial analysis of these aircraft data contained 'temporal noise' because of the finite time required to complete a flight pattern.

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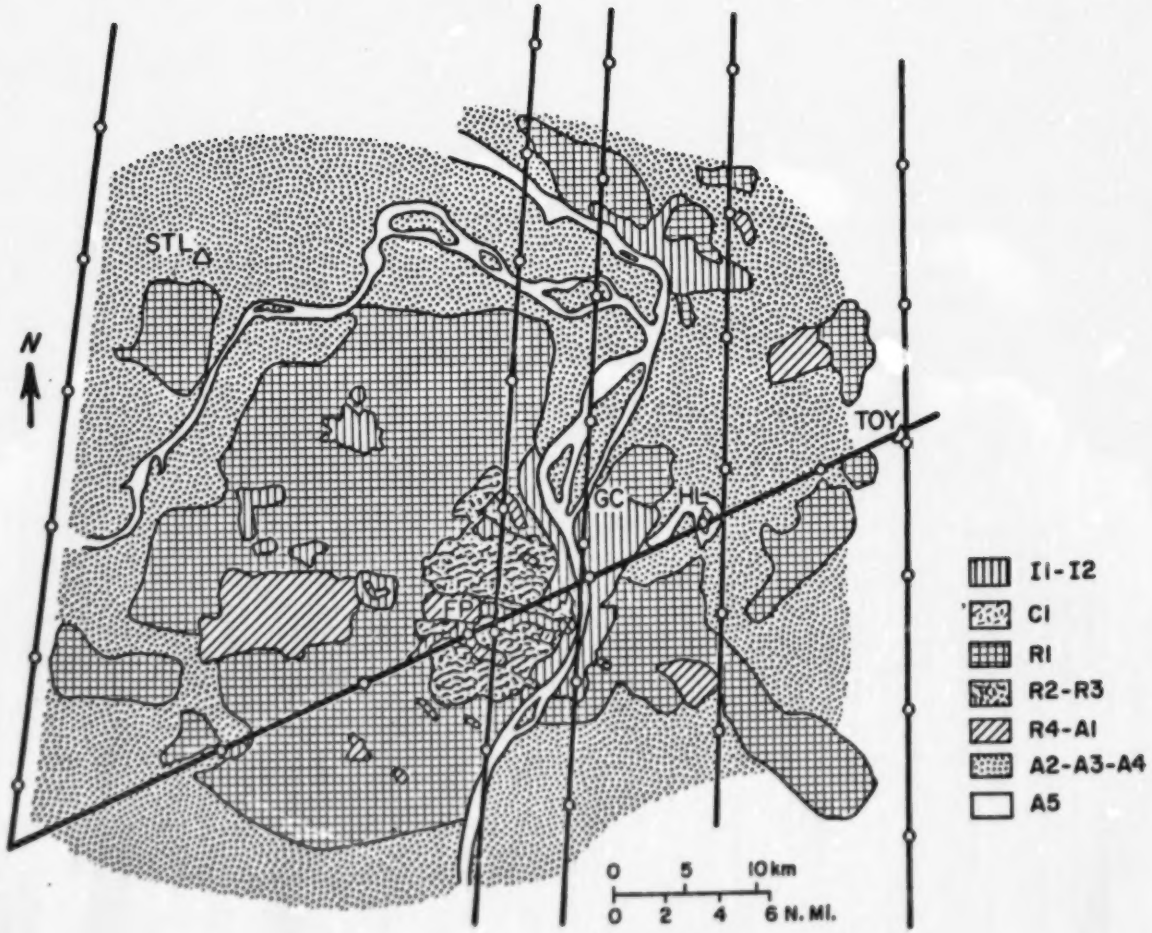

Figure 1. Land-use map of St. Louis metropolitan area (from Auer, 1978). Straight lines represent aircraft flight patterns; open circles represent the midpoint of the overlapped 22.5-km segments used in the analyses. The symbols FP refer to Forest Park, GC is Granite City and HL is Horseshoe Lake. The land use classes are I: Industrial, C: Commerical, R: Residential, A(2-4): Agricultural/rural/undeveloped and A5: Water surfaces.

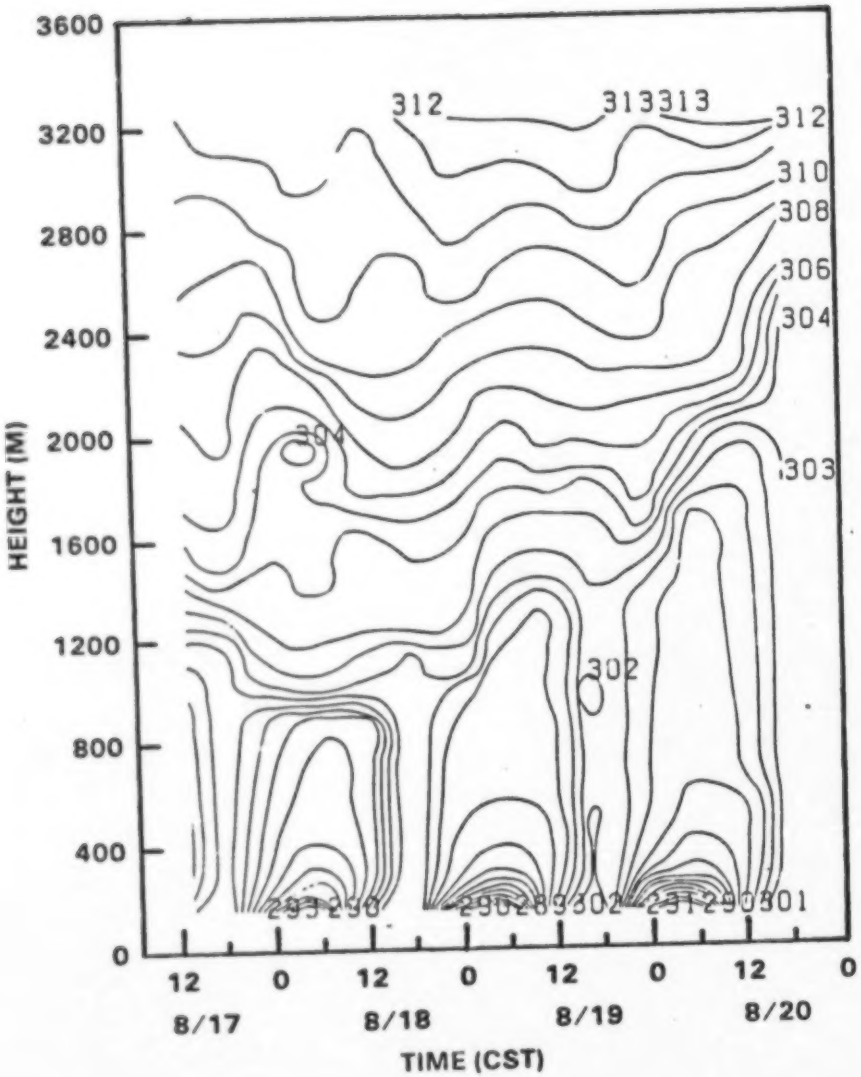

Figure 2. Time-height cross section of potential temperature for 17-20 August 1976 at a rural site 40 km southwest of the St. Louis urban area.

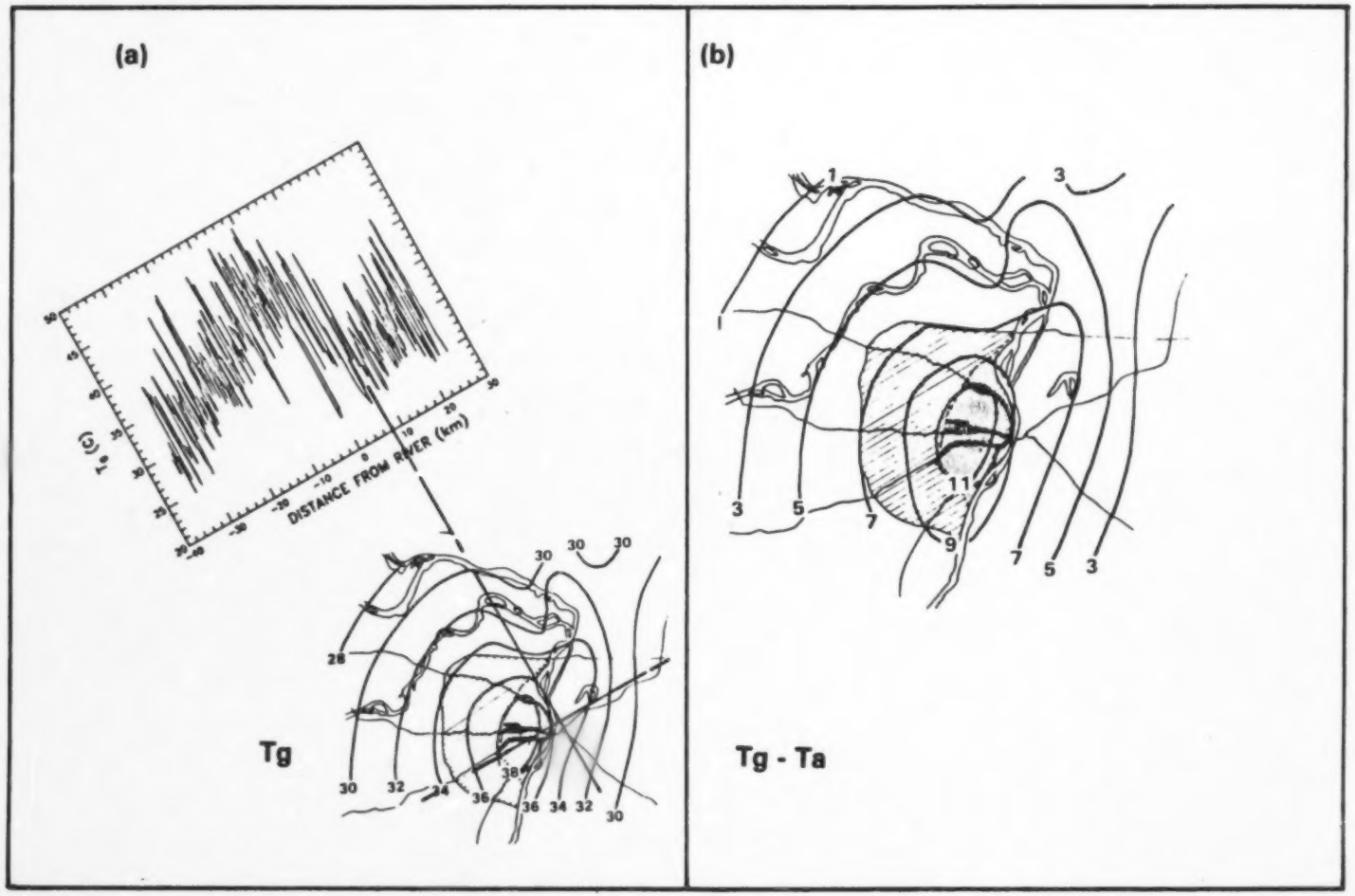

Figure 3. (a) Spatial analysis of surface temperature and the detailed time series of ground temperature on 18 August 1976, from the aircraft's downward-looking radiometer. (b) Spatial analysis of the difference between surface and air temperature (at 6 m).

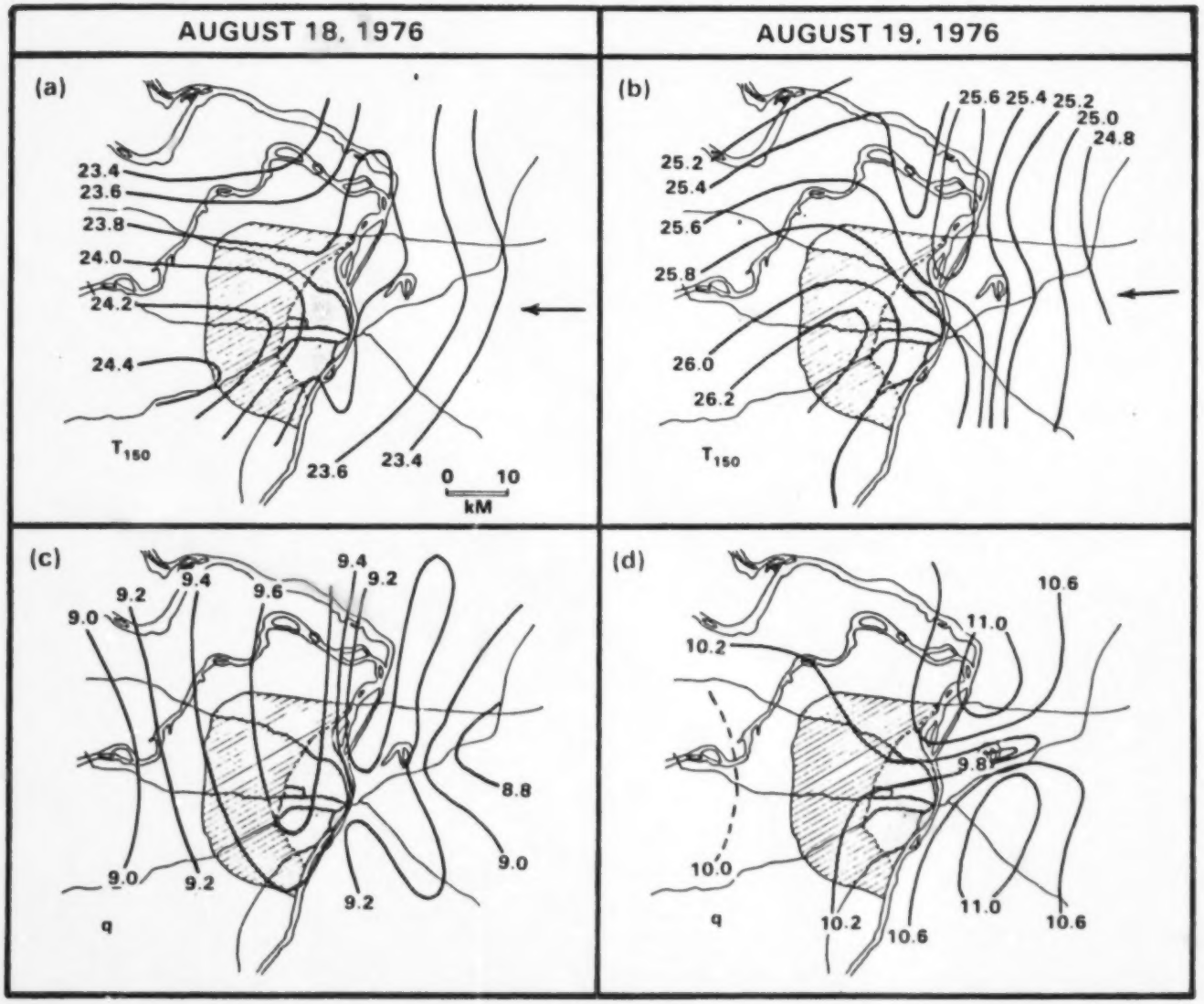

Figure 4. Spatial analysis of aircraft-derived mean temperature (^{o}C) (a and b) and absolute humidity (g m^{-3}) (c and d) at 150 m AGL on 18 and 19 August 1976.

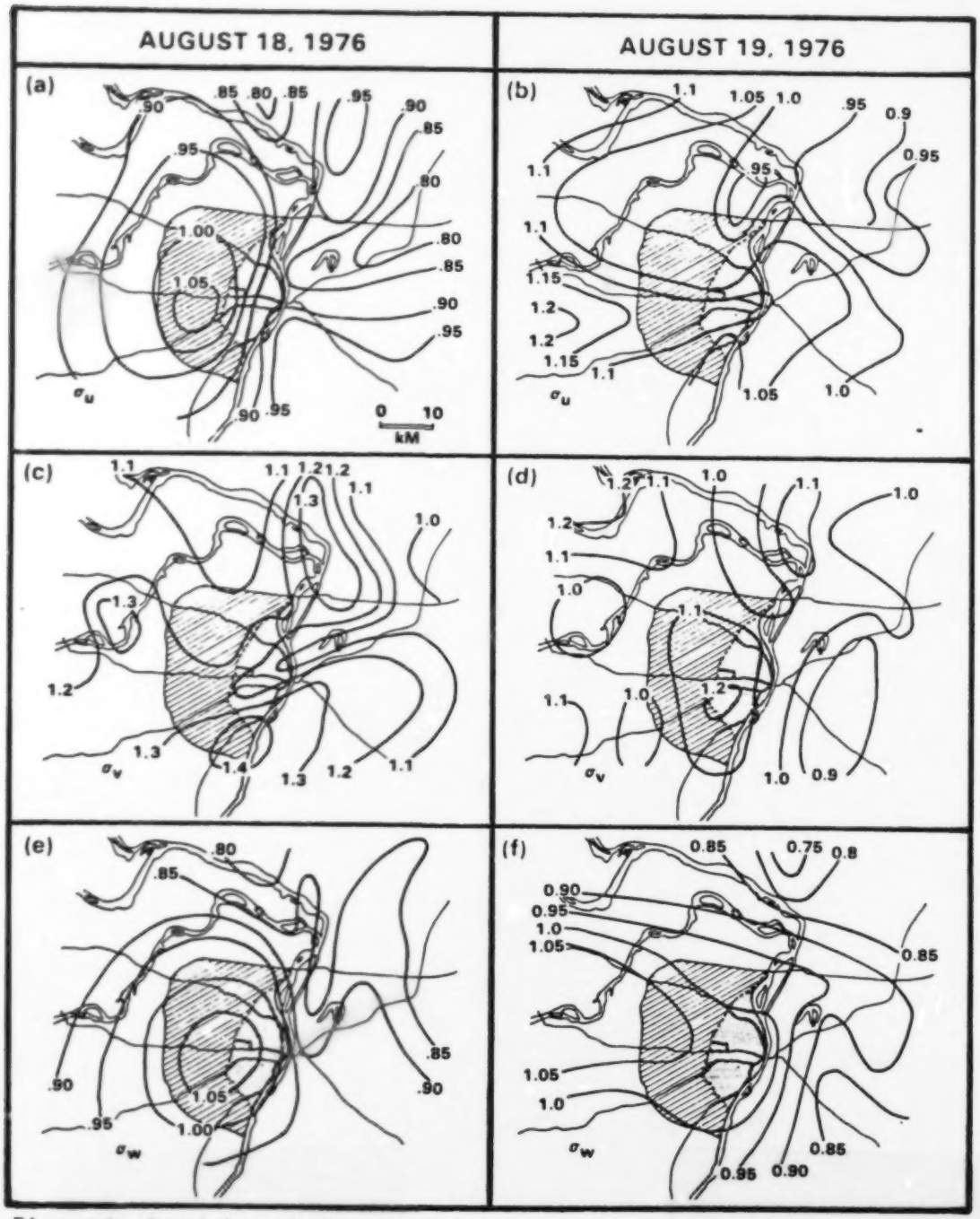

Figure 6. Spatial analyses of velocity component standard deviations, σ_u, (a and b), σ_v, (c and d), and σ_w, (ms^{-1}) (e and f) at 150 m AGL on 18 and 19 August 1976.

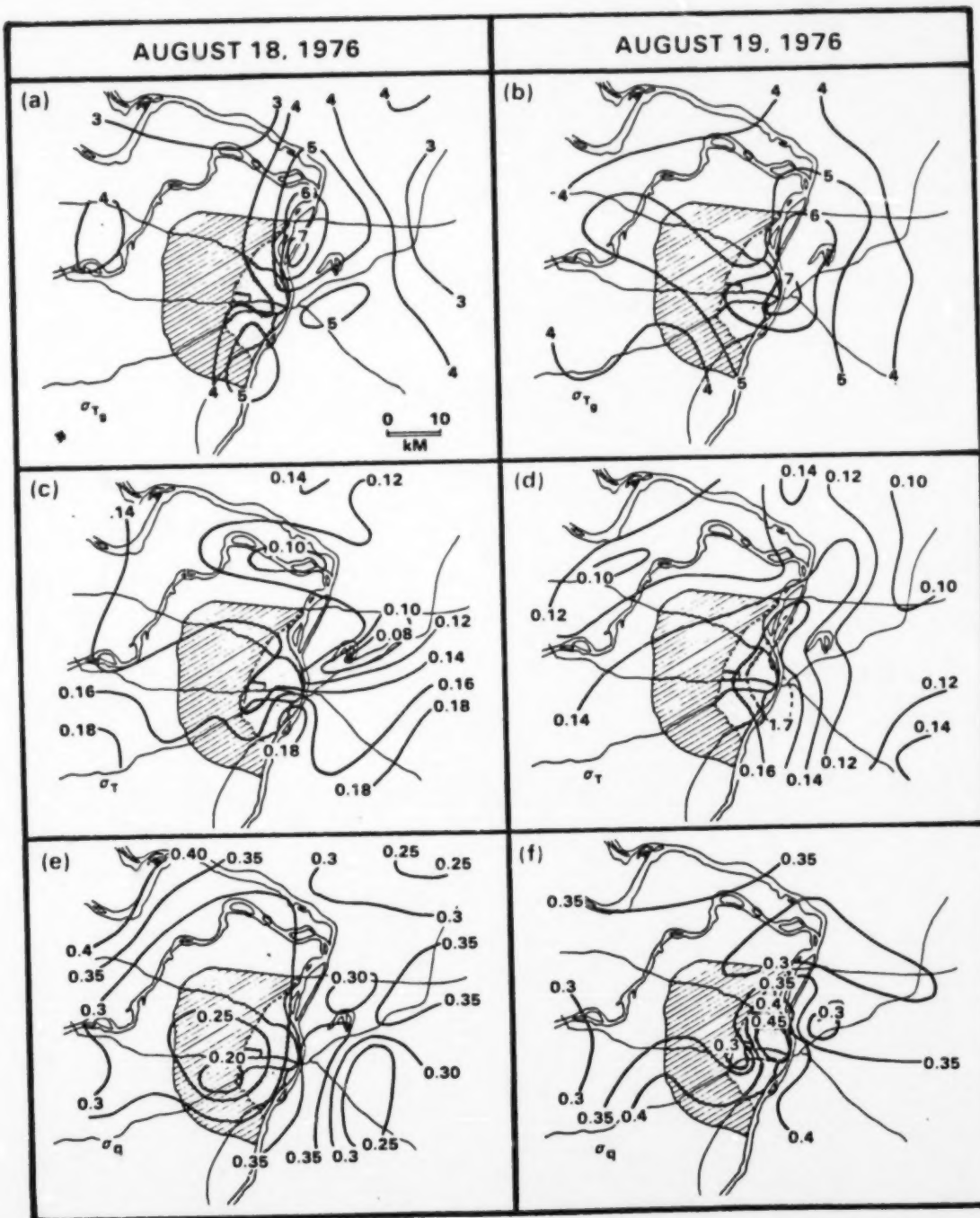

Figure 5. Spatial analyses of surface temperature standard deviation σ_{Tg} (°c), (a and b), air temperature σ_T (°C) (c and d), and absolute humidity σ_g, (g m^{-3}) (e and f) at 150 m AGL on 18 and 19 August 1976.

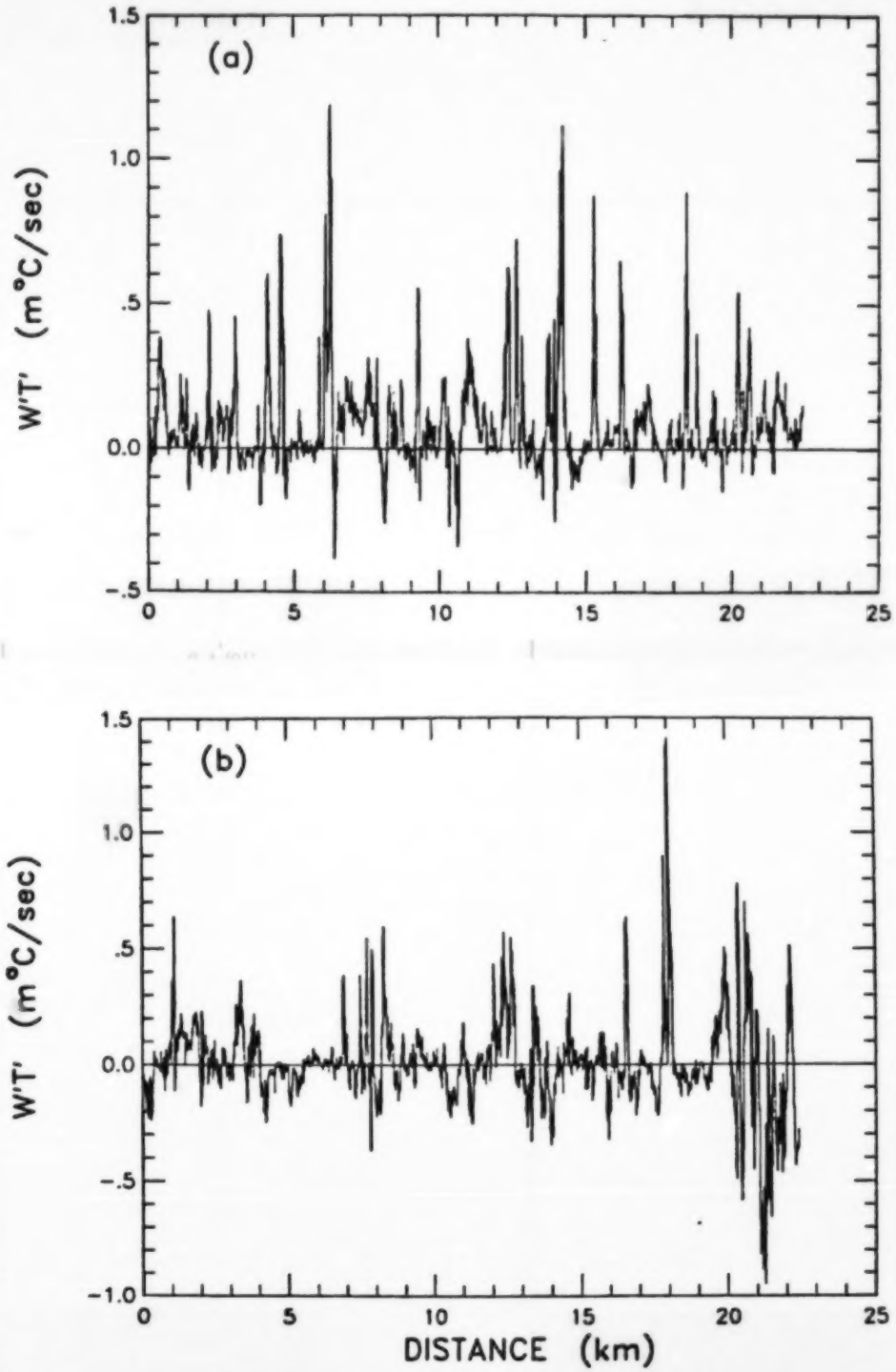

Figure 7. Covariance of temperature (T') and vertical (w') fluctuations along 22.5-km flight segments on the afternoon of 18 August 1976: south-to-north urban segment and (b) north-to-south segment over the Mississippi River and the area near Granite City.

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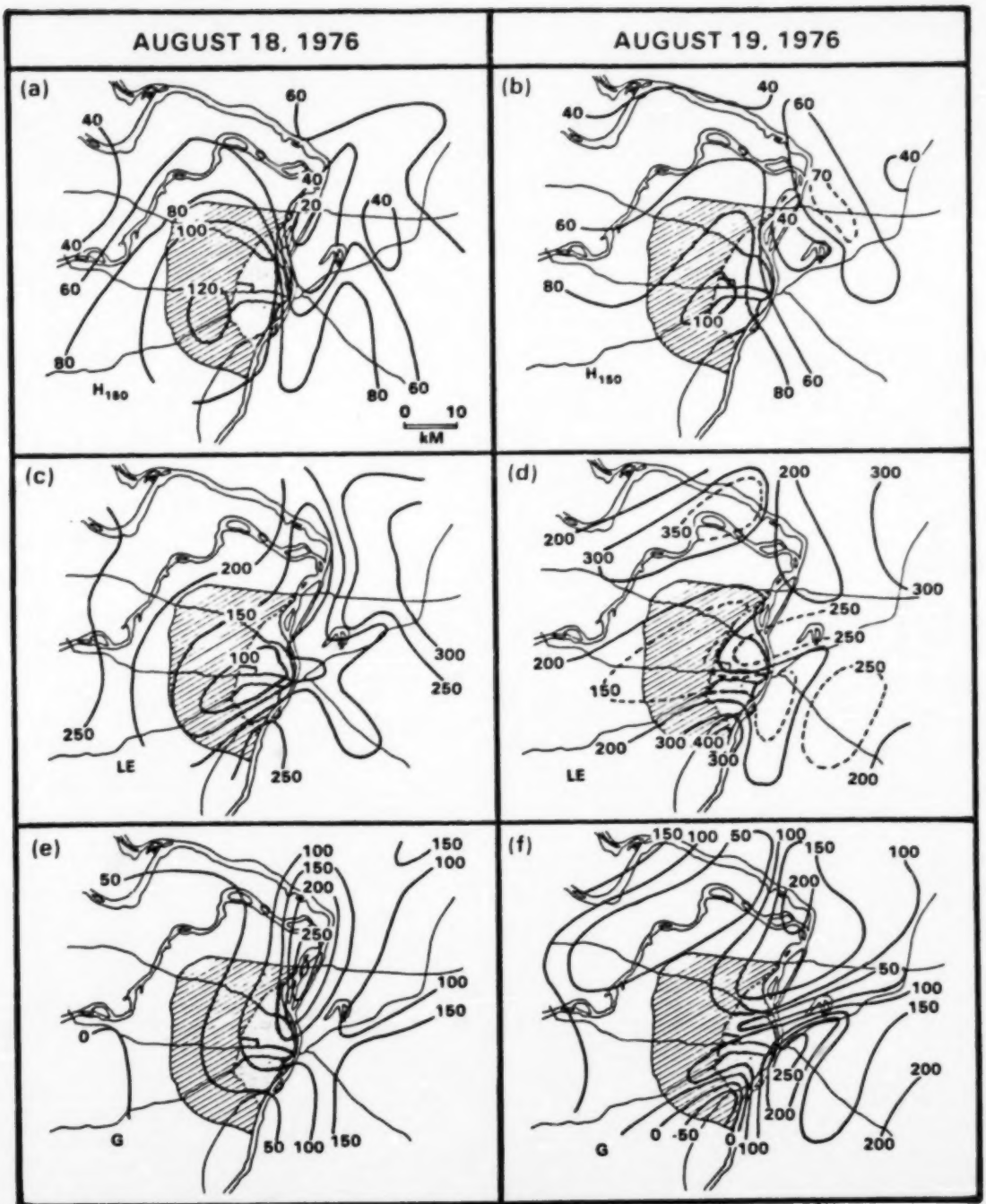

Figure 8. Spatial analyses of sensible heat flux, H, (a and b), latent heat flux, LE, (c and d), at 150 m AGL and derived ground heat flux, G (e and f) on 18 and 19 August 1976.

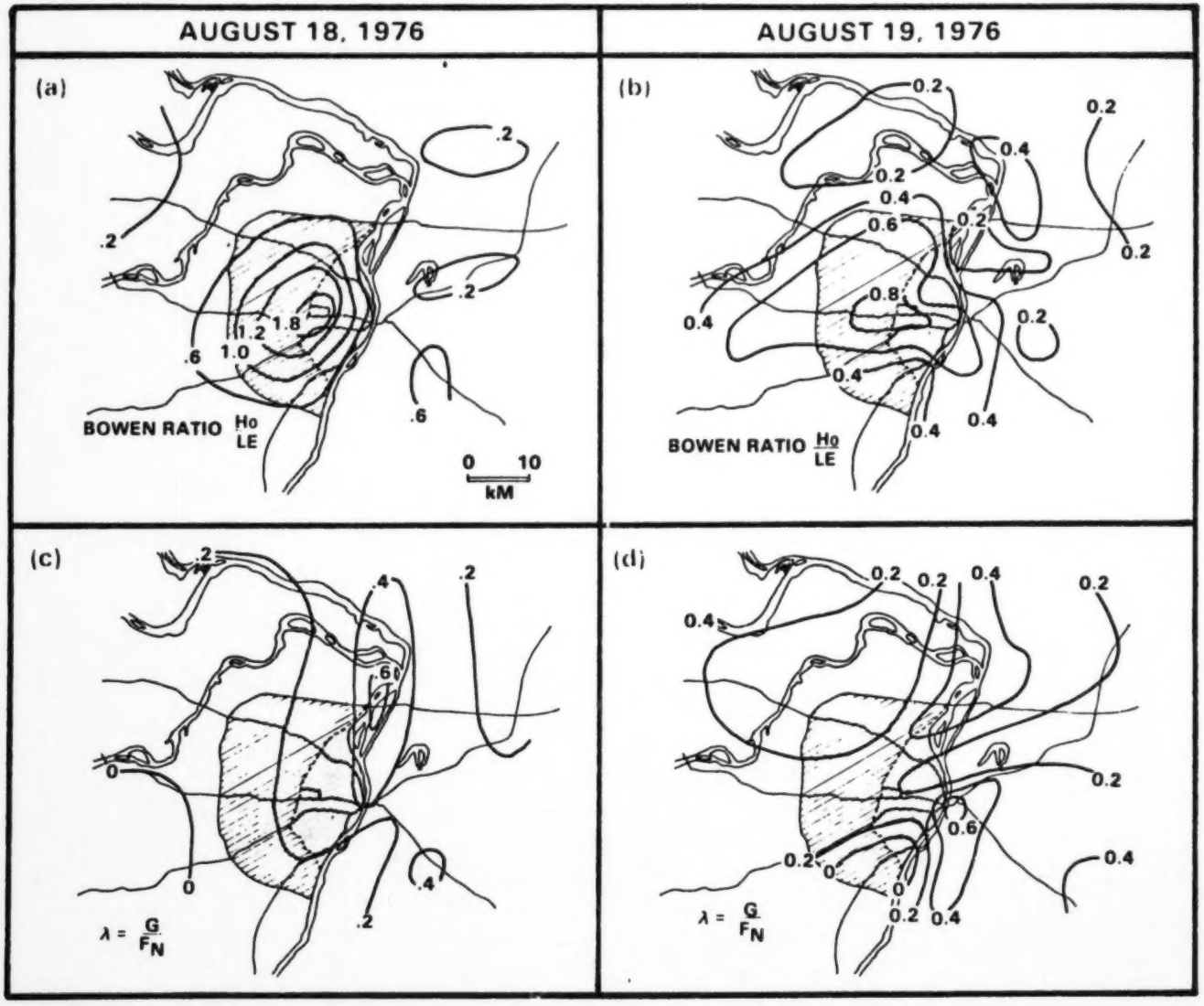

Figure 9. Spatial analyses of Bowen ratio (H_0/LE) (a and b) and (G/F_n) (c and d) on 18 and 19 Gugust 1976.

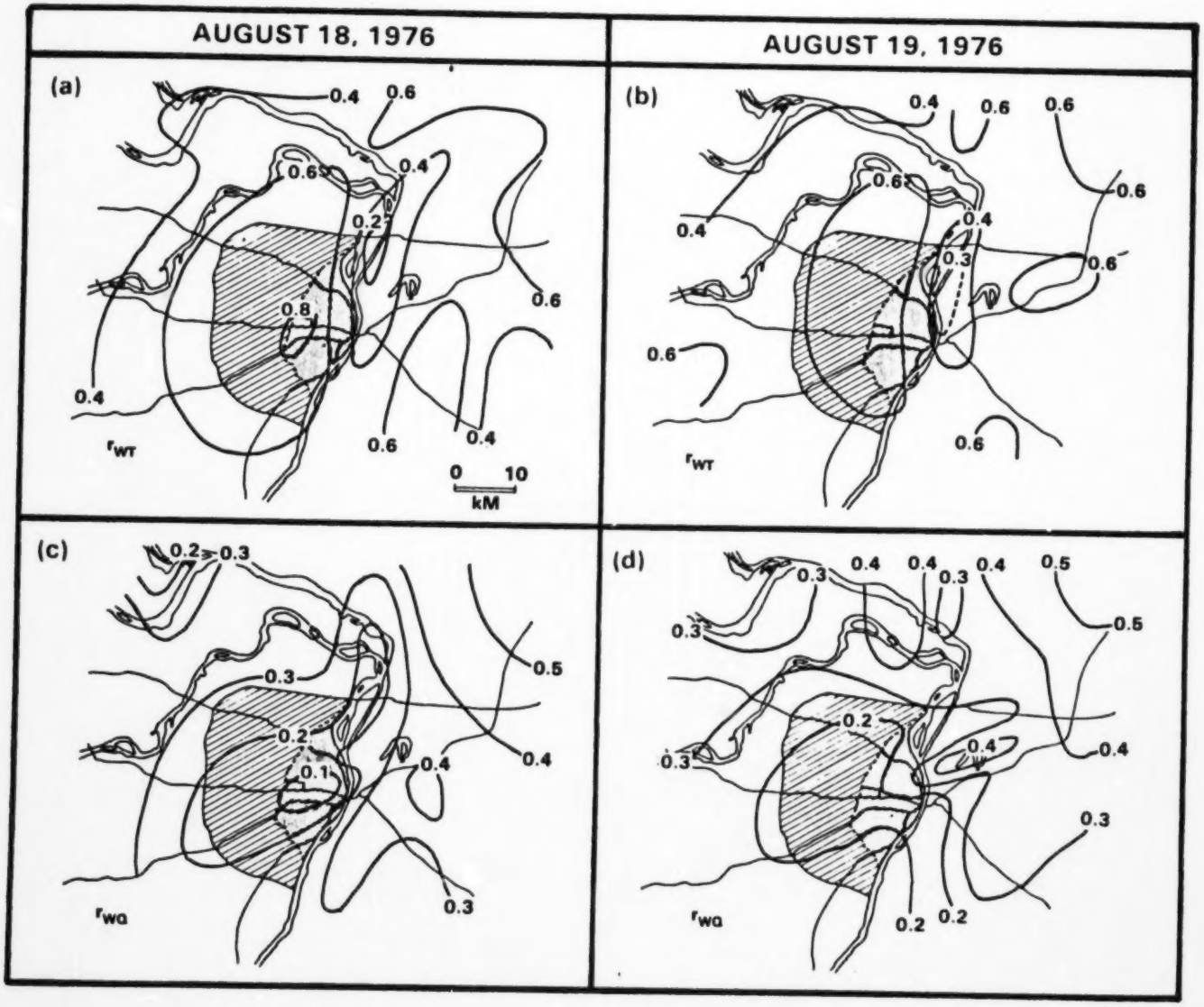

Figure 10. Spatial analyses of the correlation coefficients between w' and T' (a and b) and w' and q' (c and d) at 150 m AGL on 18 and 19 August 1976.

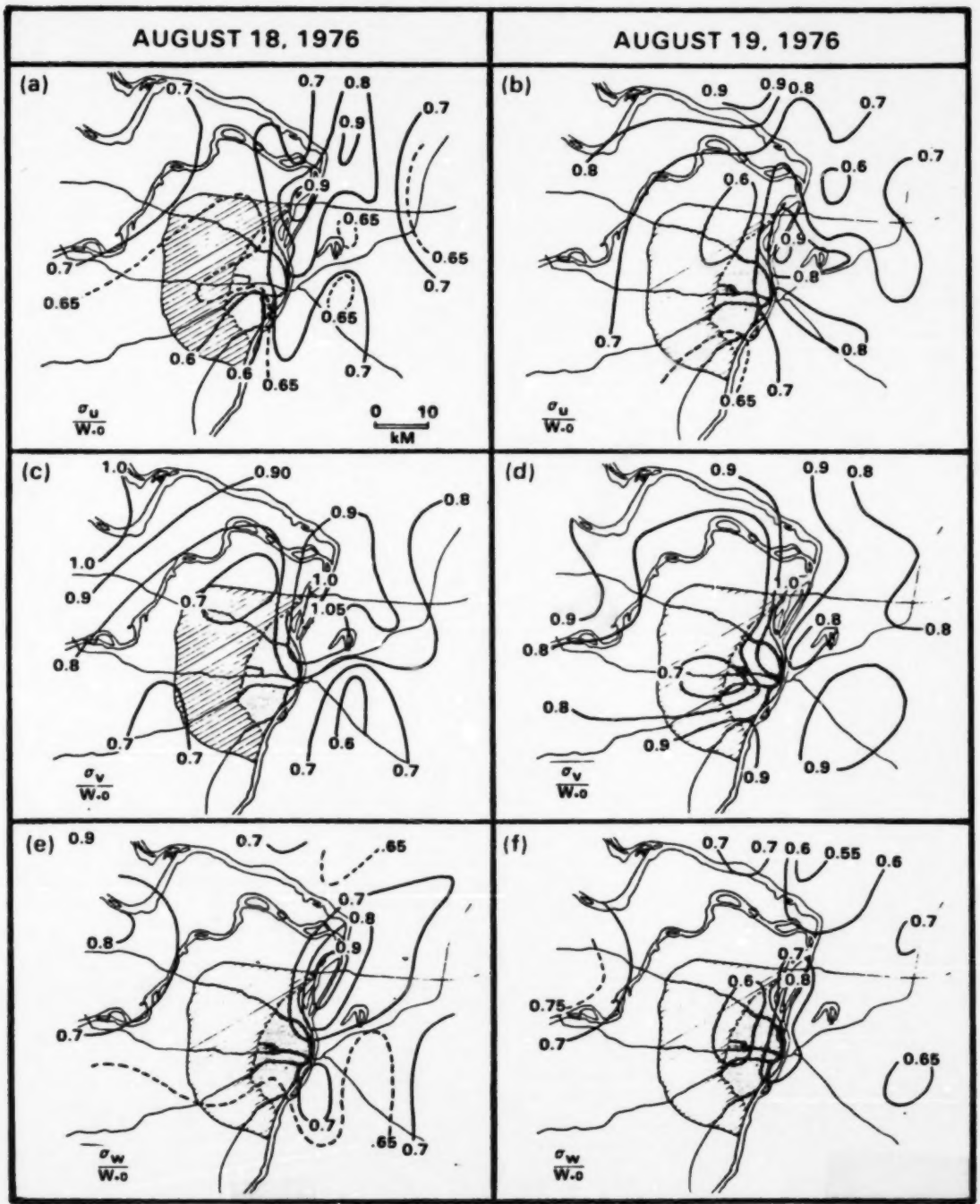

Figure 11. Spatial analyses of scaled velocity standard deviations, σ_u (a and b), σ_v (c and d), and σ (e and f), where w* was determined from surface heat flux values extrapolated from aircraft observations results at 150 m AGL on 18 and 19 August 1976.

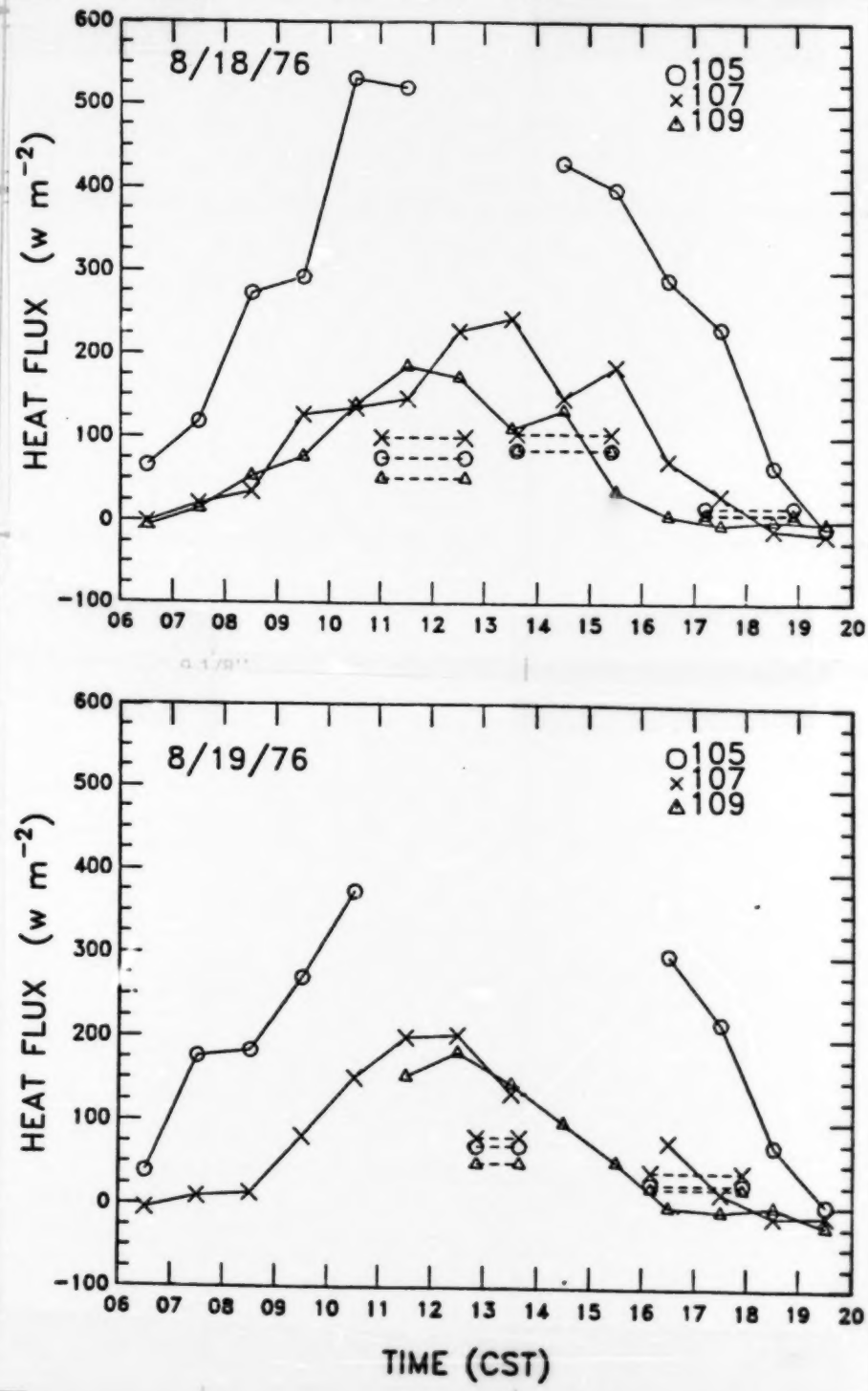

Figure 12. Time series of hourly mean surface H (w m^{-2}) at 30 m from tower eddy correlation measurements at sites 105, 107, 109; H at 150 m above the tower sites, derived from spatial analysis of aircraft measurements. H at 150 m is indicated by a horizontal bar representing the duration of the flight.